EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Spectroscopy of neutron-rich ^{122,124}Cd isotopes via d,p reactions

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Abstract: We propose to make use of the unique possibilities offered by the ISOLDE Solenoidal Spectrometer (ISS) to perform a (*d,p*) transfer reaction experiment on the neutron-rich ^{122,124}Cd isotopes. The experiment will be performed at an energy of 7.5 MeV/u in inverse kinematics. The neutron-transfer reactions will allow to study the single-particle strength for the $2d_{3/2}$, $3s_{1/2}$ and $1h_{11/2}$ states in the two-proton holes cadmium isotopes and also it will give the single-neutron strength for the *fp* shell above N=82 for the first time in cadmium isotopes.

Requested shifts: 21 shifts, (split into 1 runs over 1 years)
Installation: ISOLDE Solenoidal Spectrometer

1 Physics case

The evolution of the shell structure for nuclei with large neutron to proton ratio is an open problem in contemporary nuclear physics research. The region near the doubly magic ^{132}Sn with Z=50 and N=82, within reach of current experimental facilities, has been extensively studied. Apart from being fascinating from the standpoint of nuclear structure, nuclei in this area are known to influence the abundances of elements produced in the astrophysical rapid-neutron capture process [1]. However, despite the significant experimental progress in recent years, relevant spectroscopic data are still lacking. Transfer reactions are an excellent tool for understanding single-particle characteristics in nuclei. They enhance the population of single particle states. Moreover, the extraction of spectroscopic factors provide a measure of the single-particle strength of the populated states. This information is derived by comparing observed transfer cross sections to reaction models. The effective single-particle energy of a shell-model orbital is related to the centroid of single-particle strength for that orbital. These are essential aspects for understanding the role of various nucleon-nucleon interaction components in the evolution of shell structure. It would be very interesting to perform neutron transfer reactions on neutron-rich cadmium isotopes, with Z=48. They have identical neutrons configurations to tin but with two protons holes. One would thus expect to find similar (d,p) spectra in Cd dominated by the transfer reactions to single-neutron levels, either to the *fp* shell above N=82 or to the single particle orbitals below it. Moreover, the experimental information on excited levels for cadmium isotopes is very scarce. So far, mostly all the information on excited states comes from β-decay experiments, up to A=125 [2, 3], and fission experiments only for $A > 127$ [4, 5, 6], and β-decay experiments [2, 3]. The states built on single-neutron configurations bellow N=82 have been only tentatively identify up to A=125. Neutron-transfer study will provide of important information about their single-neutron strength for these levels. Moreover, there is large lack of information about excited levels with configurations including neutron in the *fp* shell above N=82. Those configurations are very difficult to access, since they are not favored neither in β-decay nor in fission reactions for the isotopes bellow N=82, and the experimental difficulties to measure the cadmium isotopes above it. Nonetheless, these configurations are favored in (d,p) reactions, as has been observed in the tin isotopic chain [7]. This experiment will allow to populates configurations involving a neutron in the *fp*-shell for cadmium isotopes for the first time. In this proposal, we aim to extract the single-particle strength for $2d_{3/2}$, $3s_{1/2}$ and $1h_{11/2}$ states. These low energy single-neutron states in cadmium isotopes are tentatively identified from β-decay studies [2, 3], showing an inversion between the $11/2^-$ and $3/2^+$ single-neutron states in comparison with tin isotopes. Comparison between the expected levels predicted by preliminary shell-model calculations [8] and experimental data are presented in Figure 1. These calculations indicate that the single-particle strength of these configuration is mainly concentrated in one state for each one. This scenario is very similar to the one observed in the analogous states in tellurium isotopes, with Z=52, having two protons above Sn in direct (d,p) reaction experiments, ^{129}Te [9] and ^{131}Te [10]. The spectra me assured in these studies also show spectra dominated by the states originated from single-neutron configurations at both sides of the N=82 shell gap with low fragmentation. The low energy spectra is dominated by the transfer of neutrons to the $2d_{3/2}$, $3s_{1/2}$

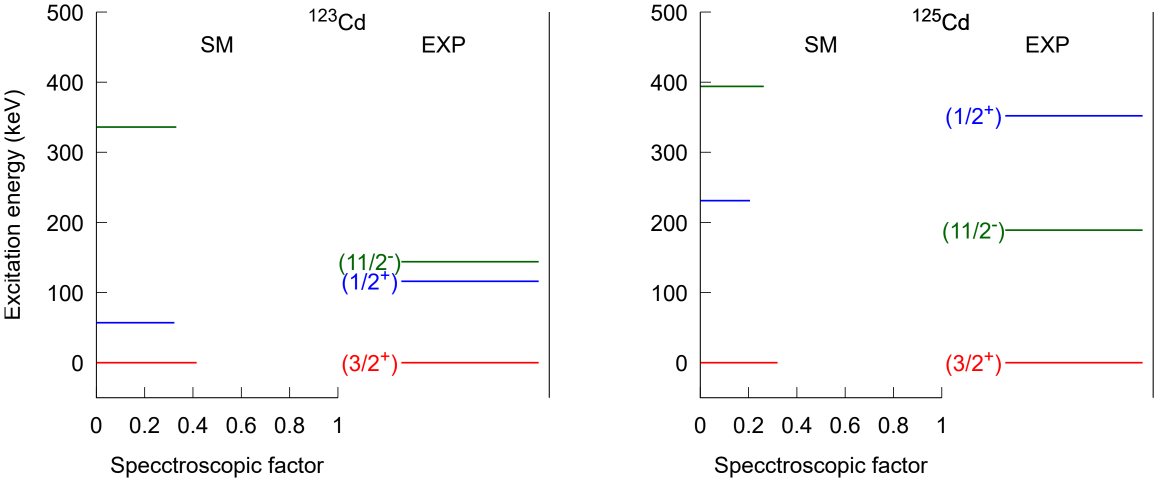

Figure 1: Preliminary shell model calculation calculations for the single-neutron states populated in the (*d,p*) reactions [8]. Only the states with an estimated S>0.1 are represented. The experimental energies for these states are obtained from β-decay studies [2, 3].

and $1h_{11/2}$ orbitals. The high energy region is dominated by the transfer of neutron to $2f_{7/2}$, $3p_{3/2}$ and $3p_{1/2}$ orbitals, showing a higher fragmentation of the levels in comparison with the case of tin isotopes. Performing (*d,p*) reactions studies will provide information on spectroscopic factors on the low-lying single-neutron states and also to study excited single-neutron excitations above N=82 in cadmium isotopes for the first time.

Neutron transfer studies have been performed on neutron-rich isotopes up to ^{132}Sn via (*d,p*) reactions [11, 7, 12]. Those reactions show spectra with a small fragmentation populating very similar Q values for all masses. Those levels are identified with pure single-neutron $2f_{7/2}$, $3p_{3/2}$ and $3p_{1/2}$ configurations where a neutron is transferred to the upper shells, above the N=82 shell gap. As can be observed in Figure 2, the states populated in neutron transfer reactions can be clearly related with the single-particle neutron states in ^{133}Sn. Removing neutrons produce a slow increase in the fragmentation of those levels, and also open the possibility of populating low-energy levels (as can be observed in the ^{126}Sn(*d,p*)^{127}Sn reaction at Fig. 2 a). The low energy states correspond to transfer of a neutron to the holes in the neutron single particle orbitals below N=82. This shows how (*d,p*) reactions for masses below ^{132}Sn, are an excellent method to study single-neutron states at both sides of the N=82 shell gap. Neutron transfer (*d,p*) reactions have also been performed for ^{124}Sn in direct kinematics [13], showing an increase in the fragmentation of the states above N=82

The investigation of neutron-rich cadmium isotopes has also an interest from the point of view of astrophysical rapid neutron-capture process. The synthesis of elements heavier than iron in the Universe is a mayor open question nowadays. The neutron r-process is the responsible for the production of half of the heavy elements [14]. Moreover, direct neutron capture is expected to have a sizable impact on the final abundances. However, experimental data are rather scarce and they often differ by orders of magnitude with the theoretical predictions. Sensitivity studies on r-process indicates that neutron capture rates of cadmium isotopes near ^{132}Sn are expected to have a sizable impact in the r-

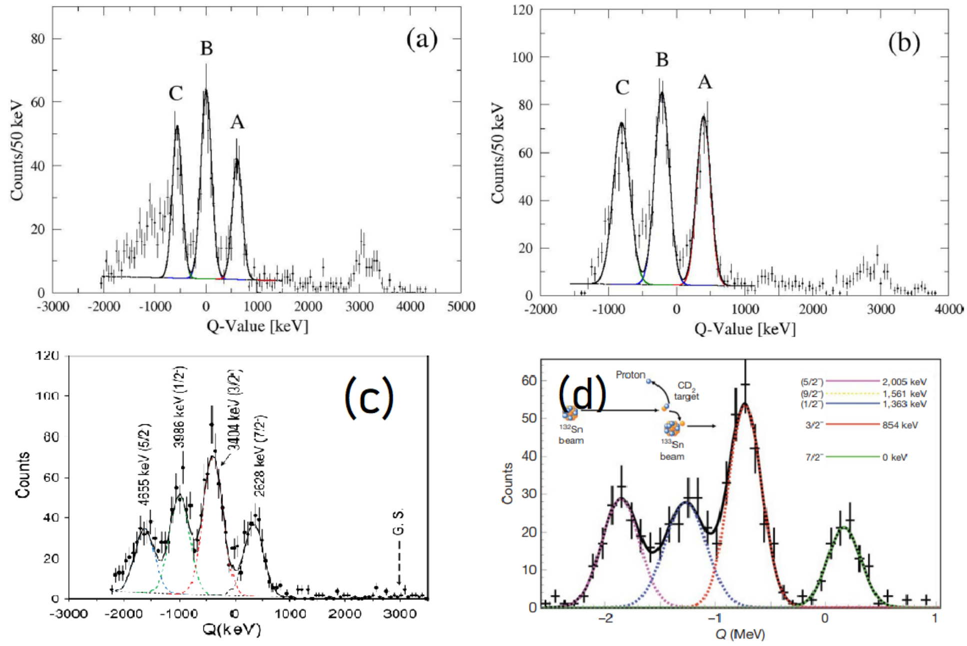

Figure 2: Systematics of the $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$ and $2f_{5/2}$ single-neutron configurations in tin isotopes populated in (d,p) reactions. The a and b panels correspond to ^{126}Sn(d,p)^{127}Sn and ^{128}Sn(d,p)^{129}Sn reactions. These figures were taken from Ref. [7]. The panel was taken from Ref. [11] correspond to the ^{130}Sn(d,p)^{131}Sn. The d panel corresponds to the ^{132}Sn(d,p)^{133}Sn published in Ref. [12].

process. Their impact becomes more important in cold r-process scenarios such as cold neutron wind driven scenario or the star merger [1], where the neutron-capture rates in cadmium isotopes with A>125 are expected to have significant impact. For the isotopes near N=82, the states with the neutrons fp shell are expected to play the an important role in the neutron-capture process. This experiment will be able to shed more information these configurations in cadmium states for the first time.

2 Experimental details

In this proposal, we aim at investigating the (d,p) reactions on Cd isotopes. We propose to measure single-neutron transfer in inverse kinematics to probe the single-particle structure in cadmium isotopes at an incident beam energy of 7.5 MeV/u. In particular, we are interested in measuring the ^{122}Cd(d,p) and ^{124}Cd(d,p) reactions.
A heavy beam is incident on a light deuterated polyethylene (CD_2) target, in inverse kinematics. The protons from the (d,p) reaction are emitted at backwards laboratory angles relative to the incident beam direction at the forward centre-of-mass angles of interest. The energy of the beam has been selected to be the one that maximize the beam intensity of cadmium at ISS.
For this measurements, the silicon array will be placed 7.5 cm far from the target, measured from the nearest detector edge. Taking into account the 0.5 m length of the detector, this setup will allow us to cover the angles comprehended in between 10° to 35°-40° for

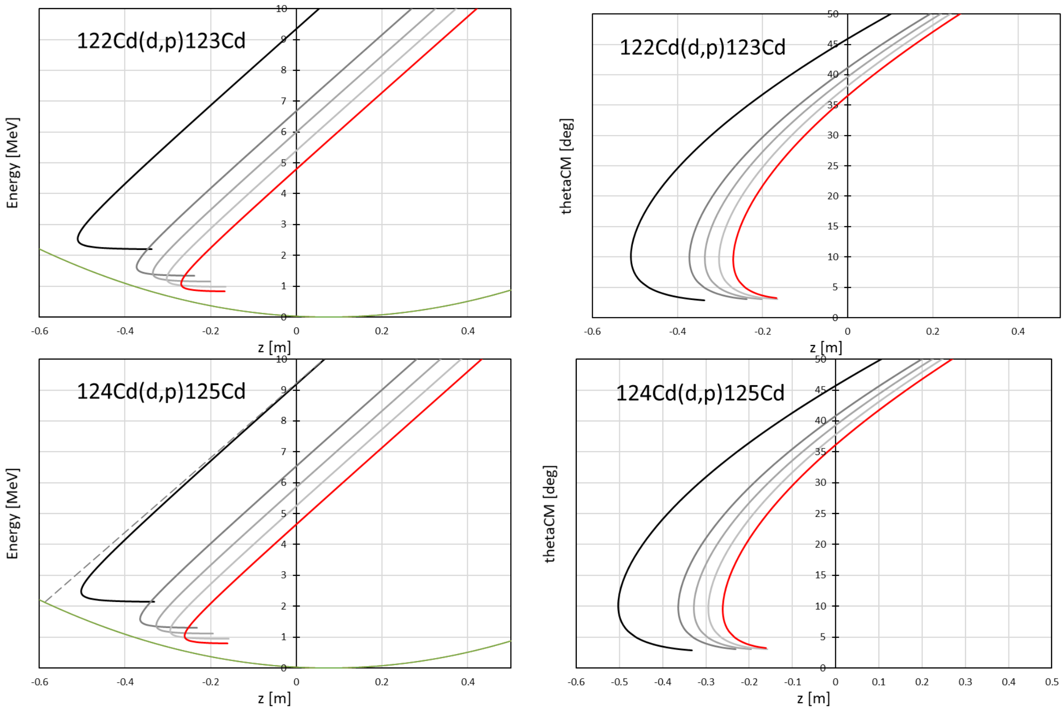

Figure 3: Energy and angular kinematics as a function of z, the position in the detector detection where it is detected. (Top) protons for the ^{124}Cd(d,p)^{125}Cd and ^{122}Cd(d,p)^{123}Cd reactions. These calculations have been performed assuming a solenoid field of 2.0 T, and beam energies of 7.5 MeV/u for both cases. The target is placed at +7.5 cm from the edge of the Si detector array. For this calculation the excitation energies for these configurations in tin isotopes were employed

the expected high energy single-neutron states, and up to 45° for the low-energy states (see Figure 3). The energy resolution for this measurement depends on the thickness of the target employed. For this experiment, we propose to use a 100 μg/cm^2 CD_2 target. Employing this configuration, an energy resolution of the order of 145 keV is expected, which is more than sufficient to separate the single neutron states that we aim to populate in this experiment. Elastically-scattered deuterons will be detected in a silicon monitor detector placed at the forward position.

Reaction cross sections for ^{122,124}Cd were calculated using the FRESCO code [15], they are presented in Figure 4. The transferred angular momenta l have been assumed to correspond to the neutron orbital angular momenta. In this calculation, only configurations with a single-neutron above the N=82 shell gap are considered. Due to the lack of systematic for the single-neutron states above N=82 in cadmium isotopes, we have employed similar excitation energies than the ones measured in tin isotopes for those levels. We have also assumed a spectroscopic factor S=1.

We request the use of a UC_2 graphite target equipped with a neutron converter to produce Cd isotopes via neutron-induced fission. The ISOLDE Resonance Ionization Laser Ion Source (RILIS) [16] with a Ta ionizer is needed for ionization. The main limitation for measuring (d,p) reactions is the one that might arise from the strong presence of isobaric contaminants. In particular, surface ionized contaminants such as indium and

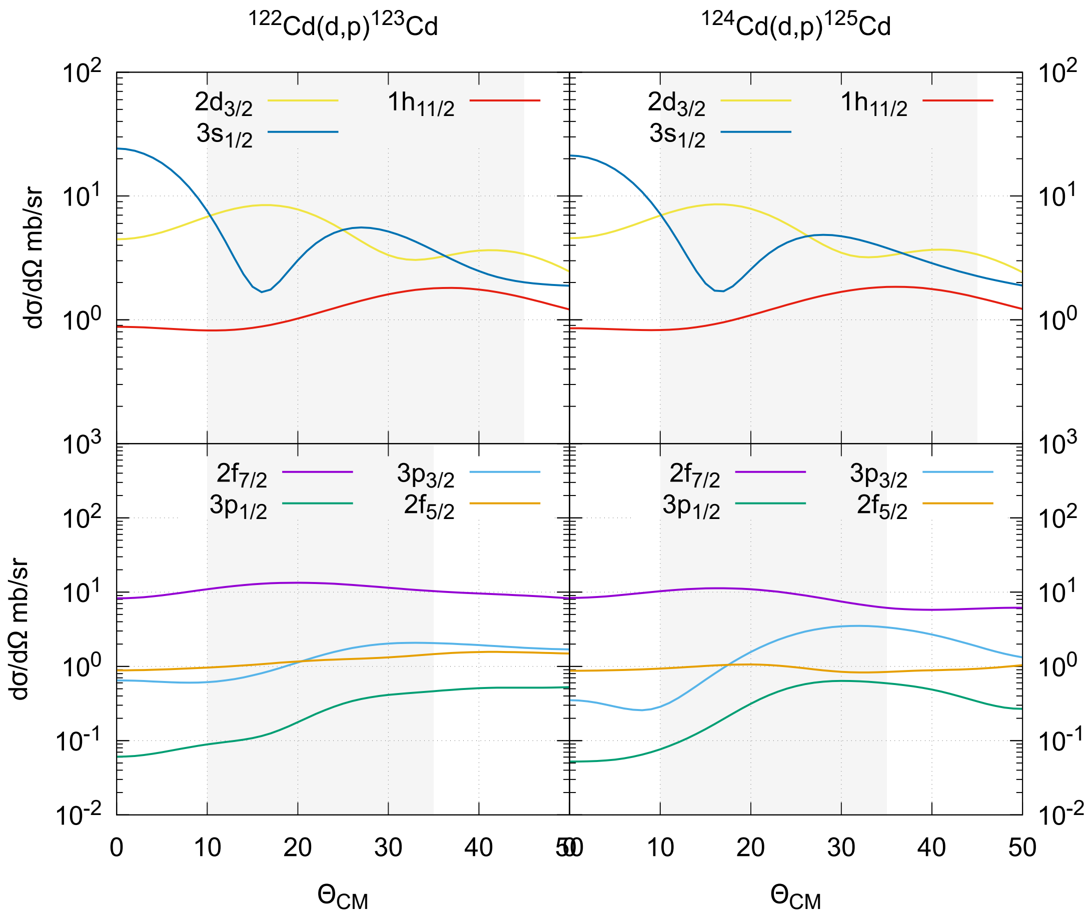

Figure 4: Angular distributions estimated using DWBA for the final states populated in the ^{124}Cd(d,p)^{125}Cd and ^{122}Cd(d,p)^{123}Cd reactions assuming S=1. The shadowed areas depicts the angular range covered by the Si-array detector.

specially cesium might dominate the beam for these masses. For this purpose, we request a temperature controlled quartz glass transfer line to suppress surface-ionized contaminants, including In, Cs and Ba. This production method has recently been used at ISOLDE for cadmium isotopes [17] and also during the recently performed IS685 experiment [18]. According to the yields obtained during the IS685 campaign using the cooled transfer line, it is not expected to have any relevant contribution of contaminants during the experiment. However, in case unexpected contamination will be present, it can be assessed by doing a laser ON/OFF measurement.

Based on the yields reported on the database and assuming reduction by a factor of 2 due to the employment of a neutron converter, we would expect yields of 3.8x10^6 Ions/μC and 1.7x10^7 Ions/μC for the ^{124}Cd and the ^{122}Cd beams respectively [20, 21]. Assuming an average proton current of 2 μA on the target, and a 3% of transmission efficiency to the ISS setup [22], we would expect an intensity at the CD_2 target of 4.6x10^5 pps for ^{124}Cd and 2.0x10^6 pps for ^{122}Cd. In table 1 the estimated counting rates per shift are summarized for both reactions. The cross sections has been estimated by integrating the

Table 1: Estimation of cross-section and the expected counting rates of protons at the ISS Si detector. See text for further information.

Reaction/ target	Intensity at ISS (pps)	Config.	J^π	Energy (MeV)	S	Δl	σ (mb)	Proton counts per shift
		$2d_{3/2}$	$3/2^+$	0	0.4	2	3.2	700
^{122}Cd(d,p)^{123}Cd	$1.0\text{x}10^6$	$3s_{1/2}$	$1/2^+$	0.116[2]	0.25	0	1.8	392
at 7.5 MeV/u		$1h_{11/2}$	$11/2^-$	0.144[19]	0.25	5	0.8	170
on 100 μg/cm^2		$2f_{7/2}$	$7/2^-$	∼2.6	0.1	3	1.3	270
		$3p_{3/2}$	$3/2^-$	∼3.4	0.1	1	0.17	36
		$3p_{1/2}$	$1/2^-$	∼3.9	0.1	1	0.03	7
		$2f_{5/2}$	$5/2^-$	∼4.5	0.1	3	0.13	28
		$2d_{3/2}$	$3/2^+$	0	0.35	2	2.8	140
^{124}Cd(d,p)^{125}Cd	$2.3\text{x}10^5$	$3s_{1/2}$	$1/2^-$	0.353 [3]	0.2	0	1.2	60
at 7.5 MeV/u		$1h_{11/2}$	$11/2^-$	0.188 [3]	0.2	5	0.6	31
on 100 μg/cm^2		$2f_{7/2}$	$7/2^-$	∼2.6	0.1	3	0.9	46
		$3p_{3/2}$	$3/2^-$	∼3.4	0.1	1	0.3	13
		$3p_{1/2}$	$1/2^-$	∼3.9	0.1	1	0.05	2
		$2f_{5/2}$	$5/2^-$	∼4.5	0.1	3	0.1	5

differential cross sections, (Figure 4), along the angular range covered by the Si array for each state. These cross sections have been scaled by the spectroscopic factors, which has been estimated from the systematic observed in the analog tellurium isotopes [9, 10].

Summary of requested shifts: We request a total number of 21 shifts for this experiment. Three shifts will be employed for the ^{122}Cd(d,p)^{123}Cd reaction, this should provide enough statistics to obtain sufficient discrimination of the angular momenta from the angular distributions of the $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$ and $2f_{7/2}$ configurations, obtaining a minimum of 500 counts for $1h_{11/2}$ state. The remaining 6 days (18 shifts), will be used to measure the ^{124}Cd(d,p)^{125}Cd reaction, and is expected to provide sufficient statistic to characterize the angular distribution for the analogous states in this isotope.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
ISOLDE Solenoidal Spectrometer	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISS installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	2 T		
Batteries	☐		

Capacitors	☐		
Ionizing radiation			
Target material	Deuterated polyethylene 100 $\mu g/cm^2$		
Beam particle type (e, p, ions, etc)	^{122}Cd and ^{124}Cd		
Beam intensity	1.7x10^7 and 3.9x10^6		
Beam energy	7.5		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☒ (α calibrations source)		
• Sealed source	☐ [ISO standard]		
• Isotope	^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cm		
• Activity	1 kBr, 1 kBq, 1 kBq, 1kBq = 4 kBq		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		

Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): N/A